Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 144 (2016) 817 – 824

Procedia Engineering

www.elsevier.com/locate/procedia

12th International Conference on Vibration Problems, ICOVP 2015

Bridge Configured Wounded Switched Reluctance Motor

Firdausa Ahmed[a], Gaurav Kumar[b], Madhurjya Dev Choudhury[b], Karuna Kalita[b,*]

[a]*Center for Energy, Indian Institute of Technology Guwahati,Guwahati-781039, India*
[b]*Department of Mechanical Engineering, Indian Institute of Technology Guwahati,Guwahati-781039, India*

Abstract

Conventional switched reluctance motors suffer from high undesired acoustic noises and vibrations caused by the production of a considerable amount of radial force due to non-uniformity in air-gap which can be controlled in order to make it more efficient. A feasible solution to pacify this problem is the introduction of a special winding scheme called bridge configured winding (BCW) in switched reluctance motor (SRM). Various winding configurations (generally dual set of windings) have been developed till date in order to produce radial force in SRM. This paper presents the incorporation of bridge configured winding capable of producing both the torque and a controllable radial force using a single set of winding, thus reducing the use of additional winding for radial force production.

Peer-review under responsibility of the organizing committee of ICOVP 2015

Keywords: Bridge configured winding; Radial forces; Switched Reluctance motor; Bearingless.

1. Introduction

A switched reluctance motor is a doubly salient motor where torque is produced by the tendency of the rotor pole to achieve a minimum reluctance position. In construction, the SRM is one of the simplest among all electrical machines. Only the stator has windings and the rotor contains no conductors or permanent magnets. It consists simply of steel laminations stacked onto a shaft. It is because of this simple mechanical construction that SRMs carry the promise of low cost.

For successful operation of SRM, it is required to switch the excitation according to the rotor position. The advances in the area of power electronics have made this switching operation more efficient which has motivated a large amount of research on SRM in the last decade. However due to its salient structure, high acoustic noise and

* Corresponding author. Tel.: +91-361-2582680.
E-mail address: karuna.kalita@iitg.ernet.in

Peer-review under responsibility of the organizing committee of ICOVP 2015
doi:10.1016/j.proeng.2016.05.091

vibration is produced. Various design methodologies of winding schemes have been introduced by researchers to produce radial force, which can be utilized for vibration suppression as well as in making the motor bearingless. Dual sets of winding was introduced by Shimada et al.[4] and Takemoto et al.[5] for bearingless switched reluctance motor where the main winding was responsible for rotation of the motor and the secondary winding for providing suspension force to the rotor. The basic concept of production of radial force using this dual winding design is that the main supply generates a 4-pole magnetic field which is responsible for the torque production and the additional winding produces a 2-pole magnetic field which is responsible for the radial force production. The flux density increases in the air gap where the direction of the 4-pole and 2-pole field is same and decreases where the pole fields are opposite. Superimposition of both of these fields produces an unbalanced flux distribution in the air-gap resulting in a net radial force in the direction of highest flux density. However, this design consumes an additional space in the stator winding which could have been otherwise used for torque production. The idea of using single winding was proposed by Higuchi and Preston and applied to a 12/8 SRM, however an account of its successful operation and control was not published [2,3]. Single layer winding for 8/6 bearingless switched reluctance motor (BSRM) was implemented by Chen and Hofmann [11] by exciting two phases together to produce both torque and suspension force. However, in 2005 a single set of winding called bridge configured winding (BCW) was introduced by Khoo [9] for polyphase self-bearing machines which could generate both torque and transverse force using the same winding. The nature of this winding was such that the currents responsible for producing torque was divided into two parallel paths and an isolated power supply called bridge currents in the midpoint of the path could produce a net lateral force. With no bridge current supply, the motor could operate as a normal torque producing machine. This design was an elegant development where no additional windings were used to produce the net lateral forces like in dual set of winding.

This present study analyzes the capability of incorporating BCW in a SRM to generate both torque and a controllable radial force, which can be utilized for vibration attenuation. Here, an analytical model incorporating the bridge configured winding in a SRM has been developed using the magnetic equivalent circuit method. Also a FE model of the SRM is designed using Maxwell 2D, which has then been used to verify the developed analytical model. The FE model is further analyzed to demonstrate the force production capability of this specialized winding scheme along with its ability to generate torque. This controllable radial force can also be utilized to convert the motor into a bearingless machine with an added benefit of requirement of low power supply for the radial force production.

2. Introduction of Bridge Configured Winding in Switched Reluctance Motor

Bridge configured winding (BCW) is a double layered, single set of winding consisting of two parallel paths. The principle feature of this winding is that the parallel path currents can be utilized for the production of force by using an isolated supply at the midpoint of these two paths. In the present study, this BCW has been applied on a SRM and its effect has been studied. Fig. 1(a) represents the circuit diagram of a single phase BCW scheme, where coil sets (1_a-$7_a'$)-(7_a-$1_a'$) and (10_a-$4_a'$)-(4_a-$10_a'$) form the two parallel paths of the winding. 1_a and $1_a'$ constitute a coil set with same number of turns and occupy one stator tooth while coil set 7 and $7_a'$ occupy diametrically opposite stator tooth, coil set 10_a-$10_a'$ and 4_a-$4_a'$ occupy stator tooth which are 90 degree apart with respect to the coil set 1_a-$1_a'$ and 7_a-$7_a'$ as shown in Fig. 2. When a current source is supplied across the point *p* and *s*, magnetic field of equal magnitude is produced along the teeth 1-4-7-10 as depicted in Fig. 2, which in turn produces a torque due the tendency of the rotor to attain a state of minimum reluctance. The speciality of the BCW scheme is that with an external isolated supply at the bridge points (a-b) and (c-d), the symmetry in the magnetic field distribution can be disturbed, which in turn results in the generation of the radial force along with the torque. Due to this external supply across the bridge points (a, b), current flows along the path (b-p-a and b-q-a), due to which the current density in teeth 1 and 10 increases, whereas it decreases in teeth 4 and 7. Thus the need of an additional set of winding for the force production is removed. Fig. 1(b) shows the formation of four pole field due to the main winding current and the formation of two pole field produced due to the bridge current which is used to create asymmetry in the air-gap.

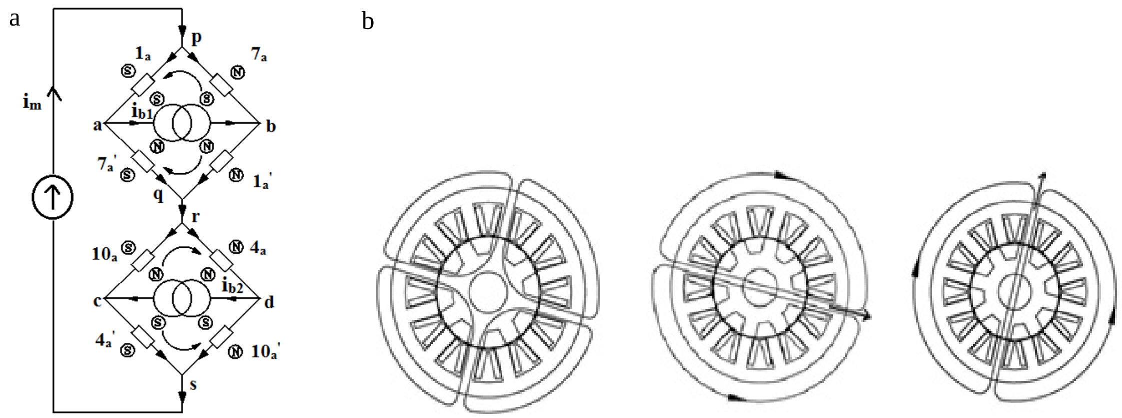

Fig 1. (a) Bridge configured winding of one phase; (b) Four pole field formation and Two pole field formation

These bridge currents can be independently controlled and its direction can be reversed, giving rise to a net radial force in any direction.

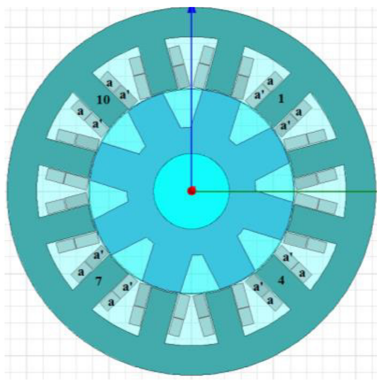

Fig 2. Cross section of motor with phase-A coils

Fig. 1(a) and Fig. 2 represent the circuit diagram of phase A and the position of the coils on the stator tooth respectively. In the present work a 12/8 switched reluctance motor has been studied, which would require a three phase connection. The connection is similar for B and C-phase winding which are situated at one-third and two-third rotational position with respect to the A-phase winding. To get the proper torque and the force profile, it is required to switch the excitation from one phase to another in a sequential manner. This switching has been achieved according to the sequence presented in Table 1.

Table 1. Switching Pattern of Coils.

Tooth excitation	Conduction angle
1-7,4-10	0 - 15^0
2-8,5-11	15^0- 30^0
3-9,6-12	30^0- 45^0

2.1. Analytical Formulation

From the preliminary design process, the stator outer diameter, rotor diameter and shaft diameter is designed. The specification of the motor is given in Table 2. Fig. 3(a) represents the magnetic equivalent circuit of a single phase (phase A) of the selected machine. As it has been discussed earlier, BCW SRM requires two supply sources for the production of the torque and the force; N_m (i_m+i_{b1}), N_m (i_m+i_{b2}), N_m (i_m-i_{b1}), N_m (i_m-i_{b2}) represent the resultant magnetomotive forces (MMFs) at the respective teeth, where N_m is the number of turns, i_m is the main supply current, i_{b1} and i_{b2} are the bridge supply currents. $\phi_{a1}, \phi_{a2}, \phi_{a3}$ and ϕ_{a4} are the magnetic fluxes of each tooth, P_{a1}, P_{a2}, P_{a3} and P_{a4} are the permeances of air-gaps. Permeance at each stator tooth air gap can be divided into three parts, one direct permeance (P_1) and two fringing permeances (P_2 and P_3) as shown in Fig. 3(b). Fringing permeance plays an important role in determining the value of inductance hence in this paper it has been modeled considering the fringing flux as elliptical lines [5].

The total permeance is thus obtained same as [5],

$$P_A = \frac{\mu_0 h_s r_r (\theta_{max} - \theta)}{l_0} + \frac{4\mu_0 h_s}{\pi} \ln\left(\frac{4ar_r\theta + \pi l_o}{\pi l_o}\right) \tag{1}$$

where, θ is the rotor rotational position, h_s is the stack length of the motor, r_r is the radius of the rotor, θ_{max} is the complete overlap position, μ_0 is the permeability of free space, l_o is the air-gap length and a is a constant of value 1.23 obtained from FEM.

Table 2. Specifications of motor.

Parameters	Values
Outer diameter of stator	120*mm*
Rotor outer diameter	62*mm*
Shaft diameter	23*mm*
Stator pole arc	15º
Rotor pole arc	22.5º
Air-gap	0.5*mm*
Stator pole height	20.26*mm*
Back of core iron thickness	8.24*mm*

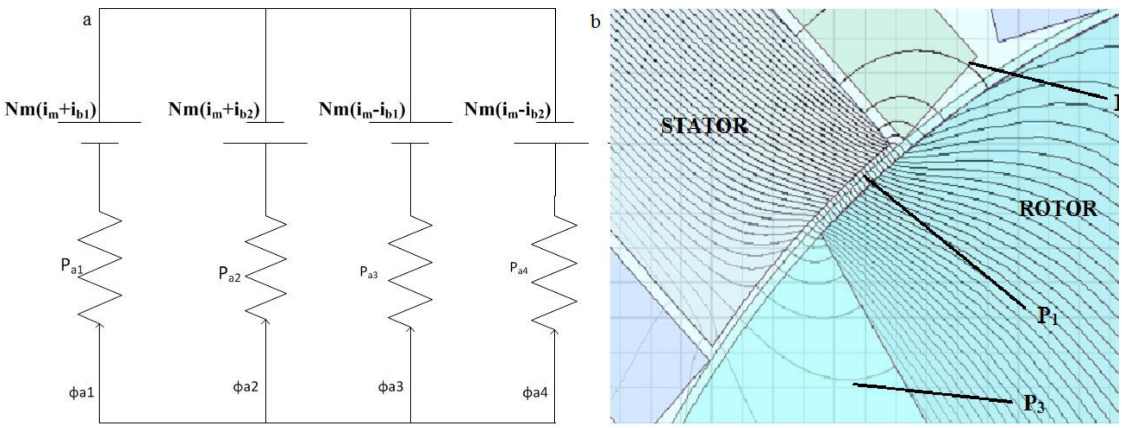

Fig 3. (a) Magnetic equivalent circuit of phase-A; (b) Flux paths and permeances

We know that the sum of magnetic fluxes through a closed surface is zero, therefore,

$$\phi_{a1} + \phi_{a2} + \phi_{a3} + \phi_{a4} = 0 \tag{2}$$

Solving the magnetomotive forces equation in each branch of the circuit and using Eq. 2, the fluxes can be written in terms of permeances as,

$$\phi_{a1} = \frac{P_{a1}}{P}[N_m(i_m + i_{b1})(P_{a2} + P_{a3} + P_{a4}) + N_m(i_m + i_{b2})P_{a2} + N_m(i_m - i_{b1})P_{a3} - N_m(i_m - i_{b2})P_{a4}] \tag{3}$$

$$\phi_{a2} = -\frac{P_{a2}}{P}[N_m(i_m + i_{b1})P_{a1} + N_m(i_m + i_{b2})(P_{a1} + P_{a3} + P_{a4}) + N_m(i_m - i_{b1})P_{a3} - N_m(i_m - i_{b2})P_{a4}] \tag{4}$$

$$\phi_{a3} = \frac{P_{a3}}{P}[N_m(i_m - i_{b1})(P_{a1} + P_{a2} + P_{a4}) - N_m(i_m + i_{b1})P_{a1} + N_m(i_m + i_{b2})P_{a2} + N_m(i_m - i_{b2})P_{a4}] \tag{5}$$

$$\phi_{a4} = -\frac{P_{a4}}{P}[N_m(i_m - i_{b2})(P_{a1} + P_{a2} + P_{a3}) + N_m(i_m + i_{b1})P_{a1} - N_m(i_m + i_{b2})P_{a2} + N_m(i_m - i_{b1})P_{a3}] \tag{6}$$

where, P is the sum of all the permeances. Using the expression $N\phi = Li$ and comparing with Eq.2 – Eq. 6 we get the inductance matrix [L] as shown in Eq. 7.

$$[L] = \begin{bmatrix} -\frac{P_{a1}}{P}(P_{a2}+P_{a3}+P_{a4})N_m^{\ 2} & -\frac{P_{a1}P_{a2}}{P}N_m^{\ 2} & \frac{P_{a1}P_{a3}}{P}N_m^{\ 2} & \frac{P_{a1}P_{a4}}{P}N_m^{\ 2} \\ -\frac{P_{a1}P_{a2}}{P}N_m^{\ 2} & -\frac{P_{a2}}{P}(P_{a1}+P_{a3}+P_{a4})N_m^{\ 2} & -\frac{P_{a2}P_{a3}}{P}N_m^{\ 2} & \frac{P_{a2}P_{a4}}{P}N_m^{\ 2} \\ \frac{P_{a1}P_{a3}}{P}N_m^{\ 2} & -\frac{P_{a2}P_{a3}}{P}N_m^{\ 2} & -\frac{P_{a3}}{P}(P_{a1}+P_{a2}+P_{a4})N_m^{\ 2} & -\frac{P_{a3}P_{a4}}{P}N_m^{\ 2} \\ -\frac{P_{a1}P_{a4}}{P}N_m^{\ 2} & \frac{P_{a2}P_{a4}}{P}N_m^{\ 2} & -\frac{P_{a3}P_{a4}}{P}N_m^{\ 2} & -\frac{P_{a4}}{P}(P_{a1}+P_{a2}+P_{a3})N_m^{\ 2} \end{bmatrix} \tag{7}$$

Since stored magnetic energy is half of the product of inductance and square of the current hence it can be expressed as,

$$W_a = \frac{1}{2}\begin{bmatrix} i_m + i_{b1} & i_m + i_{b2} & i_m - i_{b1} & i_m - i_{b2} \end{bmatrix}[L]\begin{bmatrix} i_m + i_{b1} \\ i_m + i_{b2} \\ i_m - i_{b1} \\ i_m - i_{b2} \end{bmatrix} \tag{8}$$

The torque can be derived from the rate of change of the stored magnetic energy with respect to the rotational positions as,

$$T = \frac{\partial W_a}{\partial \theta} \tag{9}$$

$$T = \frac{2N_m^{\ 2}\mu_0 h_s r_r I^2}{l_o}\{1 - \frac{16al_o}{\pi(\pi l_o + 4ar\theta)}\} \tag{10}$$

where, θ is the rotor position and I is the current. The radial forces in horizontal and vertical directions can be given by,

$$F_x = \frac{\partial W_a}{\partial x} \tag{11}$$

$$F_y = \frac{\partial W_a}{\partial y} \tag{12}$$

where, x and y are the air-gap displacements in the horizontal and vertical axes. These radial forces are dependent on the main current and the bridge current and can be controlled independently by supplying the bridge currents in the winding.

3. Results and Discussion

The developed analytical torque expression of Eq. 10 has been plotted for an excitation of 5A using the specifications presented in Table 2 for a rotation of 15 degrees (from unaligned to aligned position). A 12/8 Finite Element (FE) SRM has also been modeled in Maxwell 2D to verify the developed analytical torque expression. This FE model has been further utilized to demonstrate the force production capability of a BCW SRM without affecting its output torque. The model has been discretized using triangular element and it has 5991 elements. An excitation current of 5A has been used to obtain the torque profile of the machine. Fig.4 represents the initial (unaligned) and final (aligned) positions of the rotor teeth for a single phase excitation. It can be observed that the torque profile obtained by the analytical method closely matches with those obtained by FE analysis of the model as shown in Fig. 5.

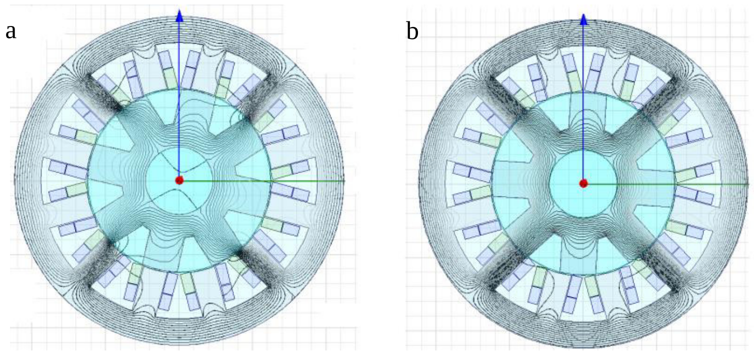

Fig. 4. (a) four pole field at unaligned position; (b) four pole field at aligned position.

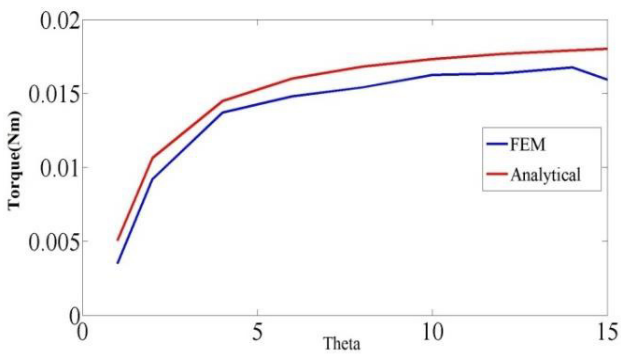

Fig. 5. Torque results from analytical and FEM

To demonstrate the force production capability, a bridge current of 2A has been supplied at the bridge points (a, b) and (c, d) while keeping the main supply current same in order to disturb the symmetric distribution of the magnetic field in the air gap. Due to this bridge supply, current density increases at teeth 1 and 10 and decreases at teeth 4 and 7. This change in current densities can be observed in terms of change in magnetic field distribution as shown in Fig. 6.

It can be observed that the magnetic flux distribution is dense at teeth 1 and 10 as compared with flux distribution at teeth 4 and 7. This obtained torque with bridge supply has also been compared to that obtained without bridge supply as shown in Fig.7.The force obtained has also been plotted for a rotation of 15 degrees as shown in Fig.8. It can be observed that there is no significant change in the torque profile. However there is an additional radial force generated, which can be used either for vibration control or for converting a conventional motor to a bearingless motor.

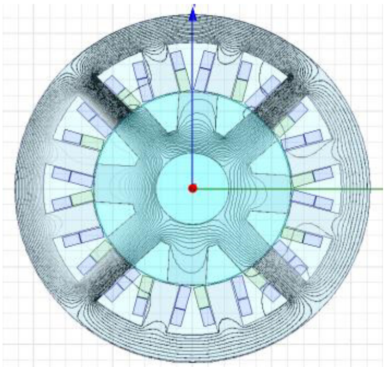

Fig. 6. Flux distribution with bridge currents

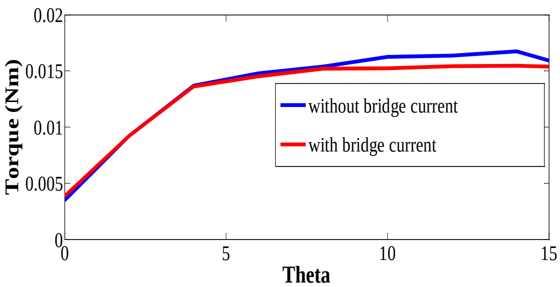

Fig. 7. Torque with and without bridge currents

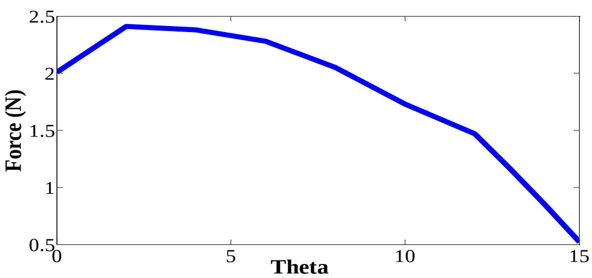

Fig. 8. Radial force with bridge currents

4. Conclusion

An analytical formulation for the torque production in BCW SRM has been developed using magnetic equivalent circuit method. Magnetic flux lines passing from the stator tooth to the rotor tooth has been divided into three regions of permeances, viz. flux lines passing directly from the stator to the rotor through the overlapped region(main flux lines) and through the non-overlapped region (fringing flux lines). Fringing flux lines has been assumed as elliptical lines whose shape has been determined using FEA in Maxwell 2D. A numerical model of 12/8 SRM has also been developed and used for validating the obtained analytical torque expression. Further, the developed numerical model has been used to demonstrate the force production capability of the BCW SRM. Variation in the magnetic field in order to generate the radial force has been achieved by supplying additional currents at the bridge points while keeping the torque producing current component as constant. This force can be used further, either for the purpose of vibration control or for the conversion of a SRM to a Bearingless Switched

Reluctance Motor (BSRM). This developed analytical formulation would be extended further for incorporating the force expression.

References

[1] R.Arumugam, J.F.Lindsay, R.Krishnan, Design Procedure for Switched Reluctance Motors, IEEE Transactions on Industry Applications, 24 (1988) 456- 46.

[2] T. Higuchi, H .Kawakatsu, T. Iwasawa, A Study on Magnetic Suspension of Switched Reluctance Motor, IEEE of Japan Annual Meeting Record, 684 (1989) 6–123.

[3] M. Preston, J. Lyons, E. Richter, E.Chung, Integrated Magnetic Bearing/Switched Reluctance Machine, U.S. Patent 5 (1994) 424-595.

[4] K.Shimada, M.Takemoto, A.Chiba, T.Fukao, Radial Forces in Switched Reluctance Type Bearing-less Motors, 9th Symposium. Electromagnetics and Dynamics, 1997, pp. 547–552.

[5] M.Takemoto, A Design and Characteristics of Switched Reluctance Type Bearing-less Motors, 4th International Symposium on Magnetic Suspension Technology, 1998.

[6] M.Takemoto, H.Suzuki, A.Chiba, T.Fukao, Improved analysis of bearing-less switched reluctance motor, IEEE Transactions on Industry Applications, 37 (1999) 26-34.

[7] A. Deihimi, A. Farhangi, G.Henneberger, A general non-linear model of switched reluctance motor with mutual coupling and multiphase excitation, Springer-Verlag, 84 (2002) 143-158.

[8] A.Chiba, T.Fukao, O.Ichikawa, M.Oshima, M.Takemoto, D.G.Dorrell, Magnetic Bearings and Bearing-less Drives, Elsevier Newnes Press, Burlington, 2005.

[9] W.K.S.Khoo, Bridge Configured Winding for Poly-phase Self-Bearing Machines, IEEE Transactions on Magnetics, 41 (2005) 1289- 1295.

[10] W.K.S.Khoo, K.Kalita, S.D.Garvey, Practical Implementation of the Bridge Configured Winding for Producing Controllable Tranverse Forces in Electrical Machines, IEEE Transactions on Industry Magnetics, 47 (2011) 1712-1718.

[11] L.Chen, W.Hofmann, Modelling and control of one bearingless 8-6 switched reluctance motor with single layer of winding structure, Power Electronics and Applications (EPE2011), Proceedings of the 2011-14th European conference, 2011.

[12] T.Halmeaho, T. Harnooja, A. Manninen, J. Pippuri, Magnetic bearing as Switched Reluctance Motor - feasibility study for bearingless Switched Reluctance Motor, IEEE International Electric Machines & Drives Conference (IEMDC), 2013.

[13] F.Ahmed, D.Saikia, S.Chaterjee, H.Singh, P.Das, K.Kalita, Self-Bearing Switched Reluctance Motor: A Review, 1st International Conference on Power and Energy in NERIST(ICPEN), 2012.

[14] A.Radun, Analytically computing the flux linked by a switched reluctance motor, IEEE Transactions on Magnetics, 36 (2012) 1996- 2003.